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Origins of energetic ions in the cusp

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Abstract. Recent studies reported on a new magnetospheric phenomenon called cusp energetic particle (CEP) events. It has been suggested that these energetic particles with significant fluxes up to several hundred keV/e are accelerated locally in the cusp. An alternative explanation for the energetic particle events is that they are accelerated at the quasi-parallel bow shock, then transported downstream and enter the cusp along newly reconnected field lines or some other solar wind entry mechanism. It is well known that shock-accelerated ions have characteristic abundance ratios, composition ratios relative to the solar wind composition, temperatures, and spectral dependency on solar wind conditions. These parameters are used to distinguish between a local (cusp) and remote (bow shock) acceleration. Our results show that average values of these parameters in the cusp are comparable to those at quasi-parallel shocks. Furthermore, changes in some of these parameters indicate a solar wind entry process that depends on energy and mass. No local acceleration is required to explain the observed CEP events up to 150 keV/e. For ions above 150 keV/e the magnetosphere itself may be responsible for the observed cusp fluxes.

1. Introduction

Entry of magnetosheath plasma across the magnetopause is an important source of plasma in the Earth magnetosphere, filling the cusp region with solar wind plasma with average energies less than several keV/e. The observed energy-latitude dispersion of precipitating cusp particles together with their D-shaped ion velocity distributions led to the conclusion that particle entry is occurring continuously on open field lines [e.g., *Reiff et al.*, 1977; *Cowley et al.*, 1991; *Onsager et al.*, 1993; *Lockwood and Smith*, 1993, 1994; *Smith and Lockwood*, 1996]. In addition to low-energy magnetosheath plasma, energetic particles of several hundred keV/e are also observed in the cusp. Possible sources of these energetic ions include the magnetosphere [e.g., *Sibeck et al.*, 1987; *Fuselier et al.*, 1991] and the quasi-parallel bow shock [e.g., *Scholer et al.*, 1989; *Fuselier et al.*, 1991].

Evidence that energetic magnetospheric ions (hundreds of keV/e) can escape the magnetosphere and are observed in the upstream region has been presented by, for example *Sarris et al.* [1976], *Krimigis et al.* [1978], and *Scholer et al.* [1981a]. The ions cross into the magnetosheath along interconnected magnetosheath-magnetosphere field lines formed by magnetic reconnection at the magnetopause [e.g., *Speiser et al.*, 1981; *Scholer et al.*, 1981b] and on a continuous basis through a leakage process at the magnetopause [e.g., *Sibeck et al.*, 1987]. Along with escape into the magnetosheath, magnetospheric ions may also enter the cusp along field lines which connect the cusp with the magnetopause (especially on the duskside) and contribute to the observed energetic cusp ions. Magnetospheric ions may also drift directly into the cusp from the magnetosphere as shown in particle simulations by *Blake* [1999].

Considerable evidence has been accumulated by the ISEE mission that the bow shock itself is the dominant source of energetic ions below 200 keV/e which leave the shock in the upstream and downstream directions. This so-called diffuse component [e.g., *Gosling et al.*, 1978; *Ipavich et al.*, 1981; *Möbius et al.*, 1987; *Scholer et al.*, 1989; *Fuselier et al.*, 1995] is associated with the quasi-parallel bow shock ($\theta_{Bn} < 45°$, where θ_{Bn} is the angle between the magnetic field line and the shock normal). *Bonifazi and Moreno* [1981] reported that almost all of their energetic particle events occurred over periods when $\theta_{Bn} < 45°$, with 75% of the events for periods when $\theta_{Bn} < 25°$ [see also *Fuselier*, 1989]. Many observed features of the diffuse ion distribution, including their general flow patterns, spectra, spatial distribution upstream and downstream of the quasi-parallel bow shock, and ion composition, have been successfully interpreted within models and simulations based on a first-order Fermi mechanism [e.g., *Lee*, 1982; *Ellison et*

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al., 1990; *Giacalone et al.*, 1992; *Scholer et al.*, 1992, *Trattner and Scholer*, 1994]. Ions undergo Fermi acceleration by scattering back and forth across the shock in the turbulence upstream and downstream from the quasi-parallel shock. A necessary condition to observe bow shock accelerated particles is magnetic connection to the quasi-parallel bow shock [e.g., *Lin et al.*, 1974]. These energetic ions may also enter the cusp from the magnetosheath [e.g., *Chang et al.*, 1998, 2000].

General methods to distinguish between a magnetospheric source and a bow shock source in the upstream and downstream region of the quasi-parallel shock are (1) studies of data intervals where specific spacecraft locations and orientations of the interplanetary magnetic field (IMF) greatly reduce the importance of one or the other source [e.g., *Gosling et al.*, 1989a; *Fuselier*, 1992] and (2) composition measurements [e.g., *Ipavich et al.*, 1984; *Möbius et al.*, 1987; *Fuselier et al.*, 1991]. Ion distributions from a magnetospheric source should be depleted in He^{2+} relative to H^+, reflecting the composition of the magnetosphere. In addition, measurements of energetic O^+ ions in upstream particle events are good indicators for a magnetospheric source, since they can be clearly distinguished from those of the solar wind [*Möbius et al.*, 1986]. Ion distributions accelerated at the quasi-parallel bow shock should contain significant amounts of He^{2+} (several percent) as well as other multiply charged ion species, reflecting approximately the solar wind composition.

A third source region for energetic ions in the cusp has been inferred by *Chen et al.* [1997, 1998] and *Chen and Fritz* [1998]. Using observations in the dayside polar cusp by the Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE) and the Comprehensive Energetic Particle and Pitch Angle Distribution (CEPPAD) instruments on the Polar spacecraft, *Chen et al.* [1997, 1998] reported particles with an ion composition similar to the solar wind composition and energies above the typical solar wind energies up to several hundred keV/e. The authors found the fluxes of energetic particles in the cusp to be substantially higher then those in the solar wind, and they concluded that these ions are accelerated locally in the cusp. These observations are interpreted as a new magnetospheric phenomenon called cusp energetic particle (CEP) events.

However, the *Chen et al.* [1997, 1998] results are in disagreement with those of *Trattner et al.* [1999], who compared two CEP events with simultaneous observations by Geotail upstream and downstream of the shock. They found a remarkably good agreement between the CEP cusp spectrum and the bow shock spectrum up to 200 keV/e and they concluded that bow shock accelerated ions can account for the CEPs observed by Polar. A similar conclusion was reached by *Chang et al.* [1998] who analyzed a 6-month database of Polar and Wind data for the northern cusp. They found that CEP events occurred mainly for $\theta_{Bn} < 45°$ and that ion spectra upstream/downstream from the quasi-parallel bow shock are similar to CEP spectra. *Chang et al.* [1998, 2000] also presented a conceptual model showing how the quasi-parallel bow shock maps into the cusp.

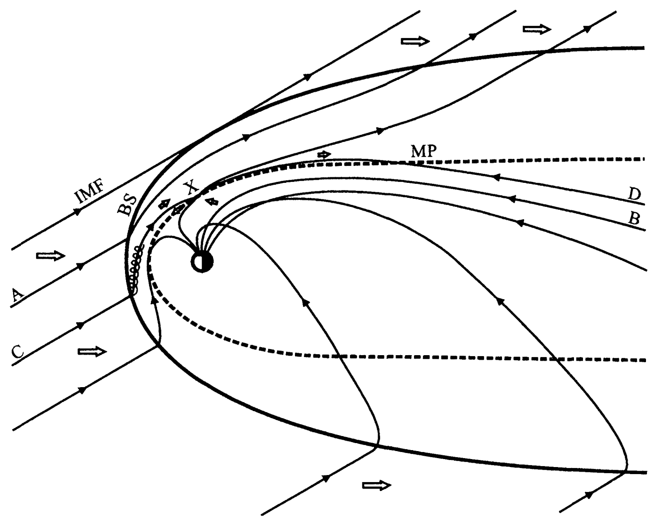

Figure 1. Schematic diagram of the magnetosphere. Heavy lines are the bow shock (BS, solid) and the magnetopause (MP, dashed). B field lines are plotted in three-dimensional perspective to show their evolution. An IMF field line, reconnected at the magnetopause, which maps back to the quasi-parallel shock region would allow access of shock-accelerated particles to the cusp [*Chang et al.*, 1998]. The IMF field lines also connect the dusk magnetopause to the cusp, allowing access of magnetosphere ions to the cusp.

Figure 1 shows a schematic view of the magnetosphere with IMF field lines which, reconnected at the magnetopause, magnetically connect the cusp with the quasi-parallel bow shock region. The observed CEP spectra can be simply explained by transporting bow shock accelerated particles from the magnetosheath along those connected magnetic field lines into the cusp. This model does not rule out a (duskside) magnetospheric source of energetic ions, since the reconnected field lines that thread the cusp connect both the quasi-parallel bow shock region and the duskside magnetopause.

Over the last decades, observations, theories, models, and simulations of quasi-parallel shocks have resulted in identifying characteristic features and predictions about those shocks and their associated energetic ions [e.g., *Gosling et al.*, 1978, 1989b; *Ellison*, 1981; *Ipavich et al.*, 1981; *Lee*, 1982; *Möbius et al.*, 1987; *Burgess*, 1989; *Scholer et al.*, 1989; *Scholer*, 1990; *Fuselier et al.*, 1990; *Fuselier*, 1994; *Kucharek and Scholer*, 1991; *Giacalone et al.*, 1992; *Trattner and Scholer*, 1994; *Trattner et al.*, 1994]. The purpose of this paper is to compare theoretical and observational features of bow shock accelerated ions to the energetic ions in the cusp to determine if the two energetic ion populations exhibit similar characteristics. Through the comparison we will distinguish possible sources of CEP ions. Specifically we will investigate (1) the energetic to thermal H^+ density ratio, (2) energetic H^+ temperature, (3) energetic He^{2+} temperature, (4) the He^{2+}/H^+ acceleration efficiency, (5) the $O^{>2+}/H^+$ acceleration efficiency, and (6) the spectral slope dependency on the solar wind velocity.

Our analysis of the six parameters mentioned above shows that average values in the cusp are similar to the average values in the quasi-parallel magnetosheath for ions below 200 keV/e. This supports the conclusion reached by *Chang et al.* [1998, 2000] and *Trattner et al.* [1999]. No additional acceleration mechanism in the cusp is required to explain the CEP events reported by *Chen et al.* [1998] below 200 keV/e. For ions above 200 keV/e there is evidence [e.g., *Sibeck et al.*, 1988; *Blake*, 1999] that the magnetosphere may be the source of the ions observed in the cusp.

2. Instrumentation and Data Selection

In this paper we present ion observations from the dayside cusp region using several instruments on the Polar spacecraft, the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) [*Shelley et al.*, 1995], the Hydra spectrometer [*Scudder et al.*, 1995], and the Magnetospheric Ion Composition Sensor (MICS) of the CAMMICE instrument (see *Wilken et al.* [1992] for a similar instrument used on the Combined Release and Radiation Effects Satellite (CRRES)). Solar wind composition measurements are provided by the Solar Wind Experiment (SWE) on Wind [*Ogilvie et al.*, 1995].

The ion distributions are observed at altitudes between 3.5 and 6 R_E in the cusp and up to 90° invariant latitude (ILAT). TIMAS composition measurements (H^+, He^{2+}, He^+, and O^+) cover the energy range from 16 eV/e to 33 keV/e and provide a 98% coverage of the unit sphere during a 6-sec spin period. The Hydra spectrometer covers the energy range from ~ 10 eV to 19 keV and samples three-dimensional (3-D) distributions of electrons and ions (assuming H^+). The MICS sensor covers an energy range from 1. to 193.4 keV/e for H^+ and He^{2+} and from 1. to 100.1 keV/e for $O^{>2+}$.

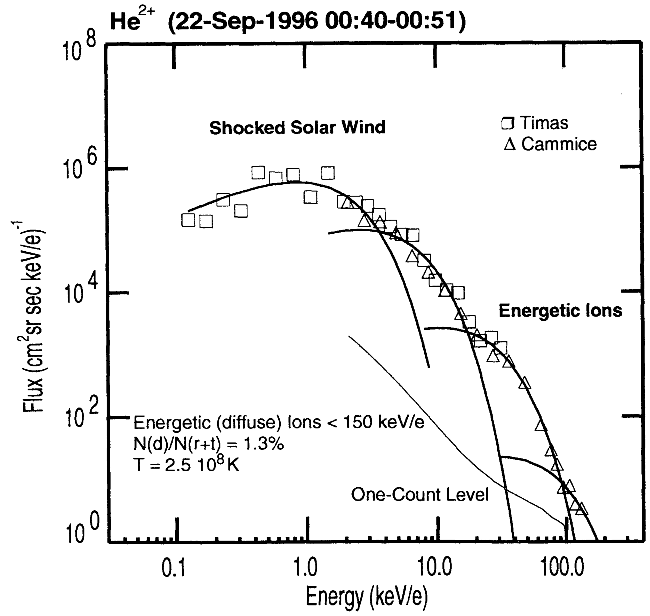

Figure 3. Spectra for the September 22, 1996, CEP event from 00:40-00:51 UT. Plotted are TIMAS (squares) and CAMMICE (triangle) He^{2+} flux values versus energy per charge. The spectra shows three characteristic breaks, separating it into four distributions which are fitted with Maxwellian functions to obtain densities and temperatures.

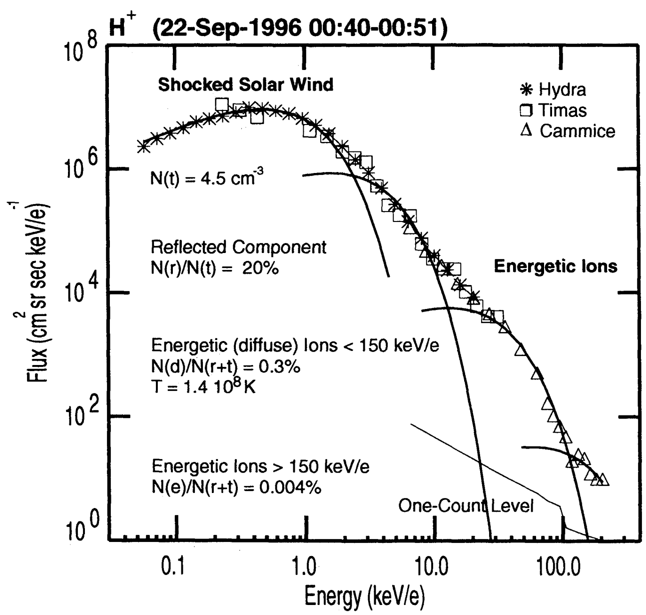

Figure 2. Spectra for the September 22, 1996, CEP event from 00:40-00:51 UT. Plotted are Hydra (stars), TIMAS (squares) and CAMMICE (triangles) H^+ flux values versus energy per charge. The spectra shows three characteristic breaks, separating it into four distributions which are fitted with Maxwellian functions to obtain densities and temperatures.

Chen et al. [1998] published a list containing 35 Polar cusp crossings. Almost all of these cusp crossings were further subdivided into as many as four CEP events which resulted in a total of 75 CEP events. On the basis of this list we selected the same time intervals to investigate the characteristic parameter discussed in section 1. A detailed analysis of the TIMAS data for the 75 CEP events revealed that some of the events contained not just cusp observations but mixtures of cusp (high ion density) and magnetic lobe observations (low ion density). Since averaging over mixed events will have a strong influence on several of the key parameters in this investigation, e.g. the ion density and temperature, we have excluded mixed events and compiled a list of 53 out of the 75 events of *Chen et al.* [1998].

Figure 2 shows a typical example of a CEP event on September 22, 1996, 00:40-00:51 UT. Plotted are H^+ flux values of Hydra, TIMAS, and CAMMICE versus energy per charge. The flux spectrum is well above the one-count level and shows several characteristic breaks at ~ 2, 10, and 150 keV/e, consistent with observations in the quasi-parallel magnetosheath and at the shock [e.g., *Gosling et al.*, 1989b; *Fuselier*, 1994]. To obtain the densities and temperatures used later in the study for the individual parts of the distribution, the flux values have been fitted with four Maxwellian functions.

The shocked solar wind (~<10 keV/e) in the quasi-parallel magnetosheath often consists of two distinct populations: (1) a cold dense core and (2) a more tenuous shell of hotter ions. The core consists of directly transmitted solar wind ions which have been slowed, deflected, compressed, and heated at the shock. The shell contains some 10-20% of the downstream ions which have been initially reflected at the shock but have made their way downstream [see *Gosling et al.*, 1989b; *Trattner and Scholer*, 1994]. The cusp spectra in Figure 2 show the same characteristics as shocked solar wind ions below 10 keV/e do, a directly transmitted distribution with a second (initially reflected) component containing $\sim$ 20% of the core distribution.

The energetic ion distributions at the quasi-parallel shock consist of (1) a bow shock accelerated diffuse ion component covering $\sim$ 10-150 keV/e [e.g., *Fuselier*, 1994; *Trattner et al.*, 1994] and under certain conditions (2) a high-energy component >150 keV/e of magnetospheric origin [see, e.g., *Krimigis et al.*, 1978; *Scholer et al.*, 1981a, *Sibeck et al.*, 1988]. The H^+ cusp spectra for the September 22, 1996, CEP event in Figure 2 again shows the same characteristics for energies >10 keV/e as the distributions at the quasi-parallel shock, including a break in the spectrum at 150 keV/e probably caused by different sources for the ions above and below this break point. It is unlikely that a single cusp acceleration process will be able to produce two distinctly different energetic cusp distributions. The density ratio of the diffuse ion, *N(d)*, to the shocked solar wind ions, *N(r+t)* is $\sim$ 0.3% with a diffuse ion temperature of 1.4×10^8 K. The density ratio of the energetic ions >150 keV/e, *N(e)* to the shocked solar wind ions, *N(r+t)* is $\sim$ 0.004%, which represents only $\sim$ 1% of the total energetic ion density. For the comparison of CEP parameters with characteristic diffuse ion parameters, we will only use the CEP energetic ion component <150 keV/e.

The combined He^{2+} spectra of TIMAS and CAMMICE for the CEP event on September 22, 1996, 00:40-00:51 UT is shown in Figure 3. The flux values are also well above the one-count level and show several characteristic breaks at $\sim$ 4, 20, and 100 keV/e, separating the spectra into shocked solar wind (<20 keV/e) and energetic ion distributions (>20 keV/e), similar to the protons. Maxwellian functions have been used to obtain densities and temperatures for the individual ion distributions.

The energetic He^{2+} cusp spectra in Figure 3 shows again the same characteristics as distributions at the quasi-parallel shock [e.g., *Fuselier*, 1994; *Trattner et al.*, 1994]. The density ratio of the diffuse He^{2+} *N(d)* to the shocked solar wind He^{2+} *N(r+t)* is $\sim$ 1.3% with a diffuse ion temperature of 2.5×10^8 K.

The $O^{>2+}$ spectrum for the CEP event on September 22, 1996, 00:40-00:51 UT is shown in Figure 4 (CAMMICE data). The flux values are close to the one-count level, which increases the uncertainty in density and temperature calculations. The density ratio of the diffuse $O^{>2+}$ *N(d)* to the shocked solar wind $O^{>2+}$ *N(r+t)* is $\sim$ 0.07% with a diffuse ion temperature of 8.7×10^8 K. No higher energetic ion population (>150 keV/e) is evident because the spectra is close to the one-count level for energies >30 keV/e.

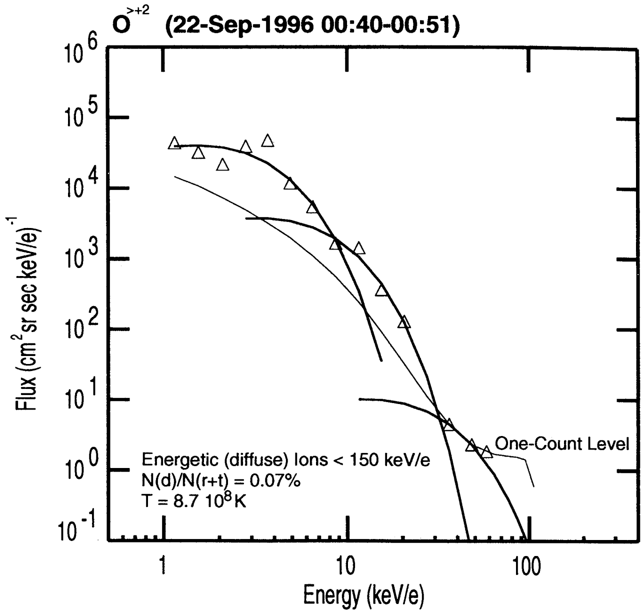

Figure 4. Spectrum for the September 22, 1996, CEP event from 00:40-00:51 UT. Plotted are CAMMICE $O^{>2+}$ flux values versus energy/e. As above with H^+ and He^{2+}, the spectrum is separated into three distributions which are fitted with Maxwellian functions to obtain densities and temperatures.

3. Density Ratio and Average Temperatures

The first energetic ions parameter investigated in this study is the density ratio of energetic (diffuse) H^+ to thermal (shocked solar wind) H^+ (see Figure 2). Figure 5 shows the normalized occurrence frequency of the energetic to thermal H^+ density ratio for the 53 CEP intervals and for the 41 AMPTE/CCE observations in the quasi-parallel magnetosheath as reported by *Fuselier* [1994]. The average values of the density ratios with 0.34% for the quasi-parallel intervals and 0.26% for the CEP intervals are similar. The occurrence frequency for the CEP intervals, however, shows an overrepresentation of low-density ratio intervals.

By comparing the energetic to thermal H^+ density ratios we need to consider that the cusp is no ordinary region. Several effects like time-of-flight effects, ions mirroring at lower altitudes and returning to the observing satellite, might influence the calculated densities, depending on the conditions in the magnetosheath (as the source of the particles) and where in the cusp the observation of energetic ions took place.

In the cusp the shocked solar wind may also contain an ionospheric component which would increase the thermal density and shift the energetic to thermal density ratio to lower values. However, using upflowing O^+ observed by TIMAS as an upper limit for upflow-

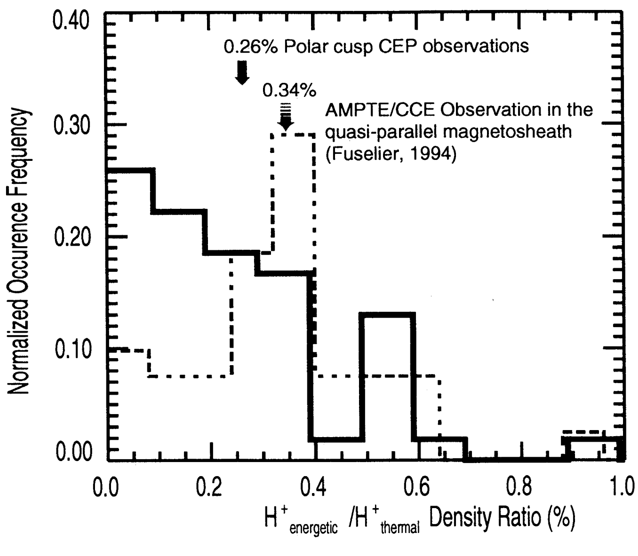

Figure 5. Normalized occurrence frequency of the energetic to thermal H^+ density ratio for cusp observations (solid line) and quasi-parallel magnetosheath intervals (dashed line). Average values are shown with arrows above their respective lines.

ing H^+ (H. Collin, private comunication, 2000), a comparison of the upflowing H^+ density with the thermal density showed only a minor contribution of $\sim 1\%$ to the thermal density.

The observed overrepresentation of low-density ratio intervals can be interpreted as an energy-dependent ion access to the cusp with higher-energy ions having a more restricted access compared to solar wind ions. There is currently no information whether energetic ions have access to the cusp in the same way as shocked solar wind ions. A systematic study of simultaneous magnetosheath and cusp observations will provide the tools to describe such an energy dependence.

The average energetic H^+ and He^{2+} temperatures for quasi-parallel magnetosheath intervals are $1.6\pm0.5\times10^8$ and $2.5\pm0.9\times10^8$ K, respectively [*Fuselier*, 1994]. These averages are remarkably similar to the average energetic H^+ and He^{2+} temperatures for the CEP events with $1.2 \pm 0.4 \times 10^8$ and $2.8 \pm 1.4 \times 10^8$ K, respectively.

4. Acceleration Efficiency

After determining the temperatures and densities of the thermal and energetic H^+ and He^{2+} distributions in the cusp, there is sufficient information to calculate the acceleration efficiency ratio for the two species. Following *Fuselier* [1994], the He^{2+} to H^+ acceleration efficiency ratio is defined as [see also *Möbius et al.*, 1987]

$$\frac{\eta_{\mathrm{He}}}{\eta_{\mathrm{H}}} = \frac{P_{\mathrm{He}} m_{\mathrm{H}} n(sw)_{\mathrm{H}}}{P_{\mathrm{H}} m_{\mathrm{He}} n(sw)_{\mathrm{He}}} \tag{1}$$

where P_{He} and P_{H} are the partial pressures of the energetic ion components of the He^{2+} and H^+ distributions, m_{He} and m_{H} are the mass of the ions, and $n(sw)_{\mathrm{He}}$ and $n(sw)_{\mathrm{H}}$ are the upstream solar wind densities of He^{2+} and H^+, respectively. The upstream solar wind densities for the CEP events are provided by the SWE instrument on Wind, and the data have been convected to the cusp.

Figure 6 shows the normalized occurrence frequency of the He^{2+} to H^+ acceleration efficiency ratio for the 53 cusp observations and the 41 AMPTE/CCE observations in the quasi-parallel magnetosheath [see *Fuselier*, 1994, Figure 10]. The distribution of the acceleration efficiency ratio for the quasi-parallel magnetosheath intervals peaks between 2 and 2.5, indicating that the quasi-parallel shock is $\sim$ 2-3 times more efficient at accelerating He^{2+} than at accelerating H^+. The average value for the CEP acceleration efficiency ratio is 2.3 ± 1.9, in agreement with the result from the quasi-parallel magnetosheath.

Note that acceleration efficiency ratio varies considerably and that the average value is dominated by several events with acceleration efficiency ratios >5. Similar to the abundance ratio above, the CEP acceleration efficiency distribution shows a significant number of events at ratios <2. The overrepresentation of low acceleration efficiency ratios for CEP events compared to the quasi-parallel magnetosheath events indicates that there is also a mass-dependent process which influences access to the cusp. Comparing the peak location in the acceleration efficiency distributions for CEP events and quasi-parallel magnetosheath, we found a 40% reduction for CEP events, which represents basically a 40% reduction in the He^{2+} to H^+ density ratio of the energetic ions compared to the ratio in the solar wind (as measured simultaneously by Wind). This 40% reduction is in remarkable agreement with the work of *Fuselier et al.* [1997], who also showed a 40% reduc-

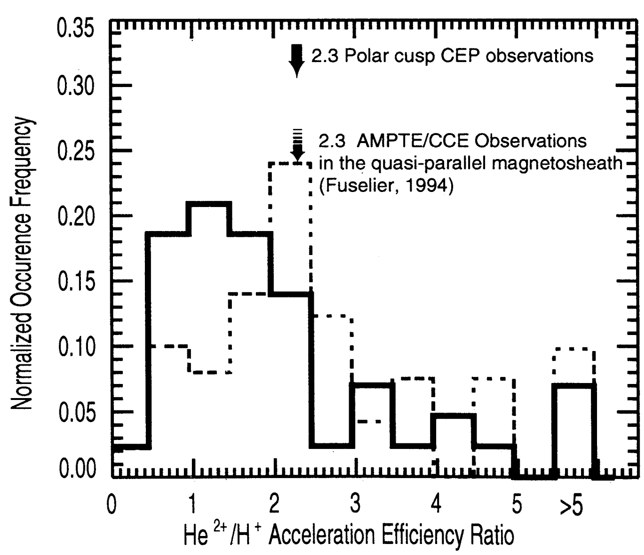

Figure 6. Normalized occurrence frequency of the He^{2+} to H^+ acceleration efficiency ratio for cusp observations (solid line) and at the quasi-parallel magnetosheath (dashed line). Average values are shown with arrows above their respective lines.

tion of the He^{2+} to H^+ density ratio from the magnetosheath to the low-latitude boundary layer (LLBL) for solar wind ions (energies approximately equal to 1 keV/e). The He^{2+} to H^+ density ratio reduction for the energetic ions is the first independent confirmation of a mass-dependent transfer process at the magnetopause suggested by *Fuselier et al.* [1997]. It further shows that the mass-dependent transfer process is independent of energy, affecting solar wind ions at $\sim$ 1 keV/e in the same way as energetic ions at > 10 keV/e.

The average value for the $O^{>2+}$ to H^+ acceleration efficiency ratio for the CEP events is 2.3±4.6, in agreement with shock acceleration theory, which predicts a ratio of 2.6 [e.g., *Ellison et al.*, 1990].

5. Solar Wind Dependency

In shock acceleration theory the exponential spectral slope of the energetic ions is correlated with solar wind parameters since the acceleration process is related to the solar wind input. In a steady state first-order Fermi acceleration process, the spectral slope is given by a power law. However, the observed diffuse ion spectra at the Earth's bow shock scales exponential in energy per charge instead of a power law [*Ipavich et al.*, 1981]. To explain such a behavior, several models [e.g., *Ellison*, 1981; *Lee*, 1982; *Forman and Drury*, 1983] have been proposed which include different loss mechanisms for diffuse ions. Although all Fermi models assume that the solar wind velocity determines the specific energy gain of the ions in the interaction with the scattering centers, only the models which include loss mechanisms predict that the solar wind velocity is related to the observed spectral slope.

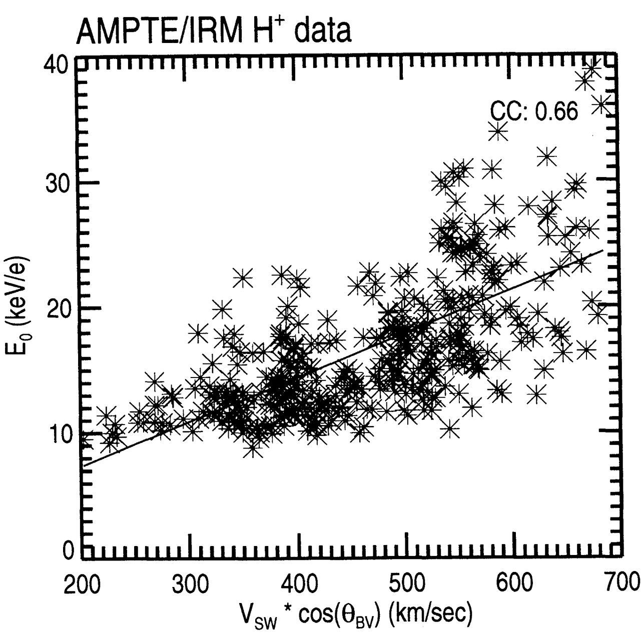

Figure 7. Correlation of the proton spectral slope E_o, determined as an exponential function in energy per charge, versus the solar wind velocity component in the direction of the magnetic field line $V_{sw}\cos(\Theta_{BV})$ for 382 events [*Trattner et al.*, 1994].

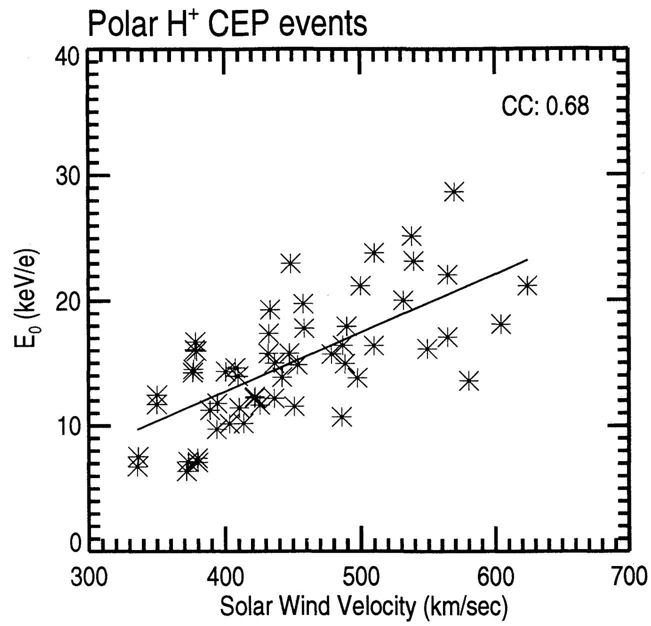

Figure 8. Correlation of the proton spectral slope E_o, determined as an exponential function in energy per charge, versus the solar wind velocity for 53 CEP events.

Trattner et al. [1994] studied the relationship between exponential spectral slope and solar wind parameters using 382 events observed by AMPTE/IRM upstream of the quasi-parallel shock ($\theta_{Bn} < 25°$). They found the best correlation with a correlation coefficient of 0.68 between the exponential spectral slope and the component of the solar wind velocity in the direction of the magnetic field (Figure 7).

The *Trattner et al.* [1994] investigation was repeated with the 53 CEP events from the list by *Chen et al.* [1998]. Solar wind velocity measurements by the Wind/SWE experiment far upstream of the bow shock have been propagated to magnetopause distance. However, to minimize the influence of propagation effects of the magnetic field components, the exponential spectral slope is only correlated with the solar wind velocity and not with the projection of the solar wind velocity in the direction of the magnetic field [see *Trattner et al.*, 1994]. Figure 8 shows the exponential spectral slopes for the energetic H^+ (<150 keV/e) versus the solar wind velocity. The linear regression returned a correlation coefficient of 0.68, the same as in the study with bow shock events above. In addition, the dependency of the exponential spectral slope E_0 from the solar wind velocity for the diffuse bow shock ions and the CEP ions is very similar, supporting also the argument that these ions are of the same origin.

6. Conclusion and Summary

After analyzing observations in the dayside polar cusp by the CAMMICE and CEPPAD instruments on the Polar spacecraft, *Chen et al.* [1997, 1998] concluded that energetic ions with energies up to several

Table 1. Comparison of Characteristic Parameters of Energetic Ions from Shock Acceleration Theory, the Quasi-Parallel Magnetosheath and the Cusp during CEP Events.

Quantity	Shock Acceleration Theory	Average Value in the Quasi-Parallel Magnetosheath[a]	Cusp Energetic Particle Events
Density Ratio $H^+_{energetic}/H^+_{thermal}$ [%]	depends on upstream parameters	0.34	0.26±0.2
Temperature $H^+_{energetic}$ [K]	depends on upstream solar wind velocity	$1.6 \pm 0.5 \times 10^8$	$1.2 \pm 0.5 \times 10^8$
Temperature $He^{2+}_{energetic}$ [K]	depends on upstream solar wind velocity	$2.5 \pm 0.9 \times 10^8$	$2.8 \pm 1.4 \times 10^8$
Acceleration Efficency He^{2+}/H^+	2	2.0 – 2.5	2.3 ± 1.9
Acceleration Efficency O^{6+}/H^+	2.67	–	2.3 ± 4.6

[a]see *Fuselier* [1994].

hundred keV/e and an ion composition similar to the solar wind composition are accelerated locally in the cusp. This new magnetospheric phenomenon called cusp energetic particle (CEP) events was challenged by *Chang et al.* [1998] and *Trattner et al.* [1999], who showed that the CEP spectra are very similar to ion spectra upstream/downstream from the quasi-parallel bow shock, a well known source of energetic particles. IMF field lines which reconnect at the magnetopause are able to magnetically connect the cusp with the quasi-parallel bow shock region. The observed CEP spectra below 150 keV/e can be simply explained by transporting bow shock accelerated particles from the magnetosheath along the connected magnetic field lines into the cusp.

In this paper we compare specific features and predictions of energetic ions accelerated at quasi-parallel shocks to observations of energetic ions in the cusp during CEP events. The results of this comparison together with predictions from shock acceleration theory are summarized in Table 1.

For the comparison we have selected 53 CEP events out of 75 used by *Chen et al.* [1998]. Only events where the Polar spacecraft remained in the cusp during the entire CEP event have been selected.

1. Using combined observations of the Hydra, TIMAS, and CAMMICE instruments on Polar in the cusp, the H^+, He^{2+} and $O^{>2+}$ flux versus energy per charge spectra show several distinctive breaks at ~ 2, 10-20, and 150-200 keV/e (see Figures 2-4). These spectral breaks are consistent with observations in the quasi-parallel magnetosheath and at the shock [e.g., *Gosling et al.,* 1989b; *Fuselier*, 1994].

2. The shocked solar wind (<10 keV/e) in the quasi-parallel magnetosheath consists of (1) a directly transmitted population (<2keV/e) and (2) ions initially reflected at the shock but convected downstream. The initially reflected ions represent ~ 10-20% of the downstream population [e.g., *Gosling et al.,* 1989b], which is consistent with CEP events used in this study with an average value of ~ 25%±10 (Figure 2).

3. The energetic ion distributions at the quasi-parallel shock consist of (1) a bow shock accelerated diffuse ion component covering ~ 10-150 keV/e [e.g., *Fuselier*, 1994; *Trattner et al.,* 1994] and (2) a high-energy component >150 keV/e of magnetospheric origin [see, e.g., *Scholer et al.,* 1981a]. The density ratio of energetic (<150 keV/e) to thermal H^+ in the quasi-parallel magnetosheath is 0.34% [*Fuselier*, 1994] which is consistent with the average density ratio of energetic to thermal H^+ in the CEP events with 0.26%±0.2 (Figure 5).

4. The average temperatures for the energetic H^+ and He^{2+} in the quasi-parallel magnetosheath are $1.6\pm0.5\times 10^8$ and $2.5 \pm 0.9 \times 10^8$ K, respectively [*Fuselier*, 1994]. These average temperatures are again remarkably close to the average energetic H^+ and He^{2+} temperatures for the CEP events with $1.2 \pm 0.4 \times 10^8$ and $2.8 \pm 1.4 \times 10^8$ K, respectively.

5. Shock acceleration theory [e.g., *Ellison et al.,* 1990] predicts a He^{2+} to H^+ acceleration efficiency ratio of ~ 2. *Fuselier* [1994] showed that the efficiency ratio for the quasi-parallel magnetosheath intervals peaks between 2 and 2.5. In agreement with these results the average value for the CEP acceleration efficiency ratio is 2.3±1.9, indicating that the quasi-parallel shock is ~ 2-3 times more efficient at accelerating He^{2+} than at accelerating H^+ (Figure 6). These observations are also consistent with Hybrid simulations by *Trattner and Scholer* [1994], who further showed that the ratio increases with increasing Mach number and increasing plasma beta.

6. The average value for the $O^{>2+}$ to H^+ acceleration efficiency ratio for the CEP events is 2.3±4.6, in agreement with shock acceleration theory, which predicts a ratio of 2.6.

7. As predicted by various shock acceleration models [e.g., *Ellison*, 1981; *Lee*, 1982; *Forman and Drury*, 1983]

and confirmed by observations from AMPTE/IRM [*Trattner et al.*, 1994], the exponential spectral slope of shock-accelerated ions increases with increasing solar wind velocity (Figure 7). Repeating this investigation with the CEP events in the cusp, the exponential spectral slope of the energetic H^+ <150 keV/e shows the same dependency with the solar wind velocity as the ions accelerated by a large-scale first-order Fermi process at the quasi-parallel shock (Figure 8).

The energetic to thermal H^+ density ratio (Figure 5) and the acceleration efficiency ratio (Figure 6) revealed differences in the CEP distribution compared to the quasi-parallel magnetosheath distributions.

There is currently no information regarding whether energetic ions have access to the cusp in the same way as shocked solar wind ions do. The overrepresentation of lower density ratio indicates that access to the cusp is energy dependent and more difficult for ions with higher energies. The energy dependency is not significant enough to affect the spectral slope of the energetic ions, since the average temperature is nearly the same in the cusp and in the magnetosheath (Table 1). Also, this energy-dependent entry into the cusp preserves the variation of the spectral slope with the solar wind velocity (Figure 8).

The overrepresentation of low acceleration efficiency ratios for CEP events compared to the quasi-parallel magnetosheath events indicates that there is also a mass dependent process which influences access to the cusp. Comparing the peak location in the acceleration efficiency distributions for CEP events and quasi-parallel magnetosheath, we found a 40% reduction for CEP events, which is in remarkable agreement with the work of *Fuselier et al.* [1997], who also showed a 40% reduction of the He^{2+} to H^+ density ratio from the magnetosheath to the LLBL for solar wind ions. This shows that the mass-dependent transfer process is independent of energy, affecting solar wind ions in the same way as energetic ions.

Further comparison of energetic ions in the cusp and magnetosheath observations together with the respective solar wind conditions could provide valuable information about energy- and mass-dependent transfer processes, the reflection coefficients for different ion species and ion energies, and the variability of plasma entry into the magnetosphere.

We have shown that there is a remarkable agreement between average values and solar wind dependencies of CEP events with their respective results from the quasi-parallel magnetosheath. The fact that all of these tests show the connection between CEP events and quasi-parallel magnetosheath provides strong support that CEP ions below 150 keV/e are simply ions accelerated at the quasi-parallel shock and subsequently transported into the cusp along reconnected magnetic field lines (see Figure 1) [*Chang et al.*, 1998].

Figure 2 shows that there are also ions with energies >150 keV/e present in CEP events. However, these ions account for only ~ 1-2% of the total energetic ion density and ~ 10% of the total pressure. *Sibeck et al.* [1988] reported H^+ particle fluxes in the low-latitude boundary layer which are of the same order of magnitude as the >150 keV/e energetic ions in CEP events. In addition, *Blake* [1999] numerically traced the motion of 800 keV/e alpha particles in several current models of the geomagnetic field and showed that ions can make several revolutions around the Earth, passing through the cusp region on the dayside and remaining trapped in the magnetosphere for 2-3 hours. Furthermore, when field parameters are appropriately changed when the ion is in the cusp, the ion can remain on the dayside and be seen mirroring at high latitudes. Also ions from the interplanetary medium can become trapped in the cusp for many minutes. *Blake* [1999] concluded that no local acceleration is required to explain the observed ion fluxes at energies > 150 keV/e.

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